

Influence of web openings on bearing capacity of triangularly corrugated web beam

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Abstract. The paper presents a study on the behaviour of corrugated web steel beams with and without web openings. Examined steel beams consist of two flanges and a thin triangularly corrugated web, connected by automatic welding. In the literature, the web opening problem in steel beams was dealt with mostly for steel beams with plane webs and research of the effect from opening in a corrugated web was found out to be very limited. A finite element analysis in ABAQUS software was carried out to investigate the effect of openings in corrugated web. A number of beams FE models comprise of web openings with different sizes and positions were developed. The effect on beam bending capacity of circular opening in corrugated web is studied for various openings positions and sizes also as corrugation density. The stress concentration factors are obtained near the circular opening in cases of its location in zone of pure bending and in zone of transverse bending of the beam. Recommendations are given for practical design of corrugated web beams weakened by circular openings.

1. Introduction

Corrugated web beams are fabricated girders with a thin-walled corrugated web and flanges made of plate steel, hollow profiles, electric welded pipes or reinforced concrete elements. Currently, such structures are used as beams of ceilings in multi-storey apartment houses, large span roof beams in industrial buildings, dome elements in administrative buildings.

In the world practice of construction, sections with trapezoidal and sinusoidal corrugation profiles are most widely used, but on territory of former USSR more often are used sections with triangular profile of corrugation is shown in figure 1. Such type of corrugation has a number of advantages over others. For example, for the production of such webs, expensive equipment is not required, and the webs can be made thicker than sinusoidal ones. This is especially important for Russian operating conditions, which are characterized by aggressive environment and large snow loads on the roof structures.

Due to its profiled form, corrugated web exhibits enhanced shear stability and therefore eliminate the need for additional transverse stiffeners or thicker web plates. The profiling of the web generally avoids failure of the beam before the web ultimate load is reached by web yielding. A distinctive feature of beams with a corrugated web is the almost complete perception of the bending moment by the flanges, and the normal stresses along the height of the web are significant just in narrow areas near the flanges and insignificant for most of the web height.



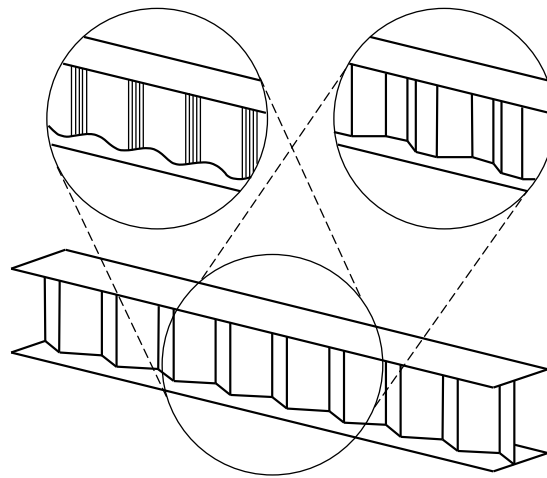


Figure 1. Beam with sinusoidal, trapezoidal and triangularly corrugated web

In structures of industrial and civil buildings for operational reasons, it is necessary to lay ventilation, heating, water supply and other pipelines, which requires making holes in the beam webs. Near the opening in the corrugated web there is a concentration of stresses, with the greatest stresses being several times greater than the so-called "medium stresses", which can cause to the destruction of entire structure.

The present paper deals with the effect of web openings on the transverse and bending load carrying capacity of steel beams with triangularly corrugated webs. In the literature, the web opening problem in steel beams was dealt with mostly for steel beams with plane web plates. Estimation of stresses in plane web of beam in conditions of pure bending and shear has been solved theoretically by Howland and Stevenson in 1933 [1]. Their results were confirmed by subsequent full-scale tests by the method of photoelasticity.

Research studies on the effect of an opening on a corrugated web were very limited. Also currently practically no design guidance is available for corrugated steel webs with web openings. Limited research on the topic includes studies by Lindner and Huang in 1994 [2], by Romeijn, Sarkhosh and Hoop in 2009 [3], by Kiymaz, Coskun E, Coskun C and Seckin in 2010 [4]. Lindner and Huang [2] were carried out an investigation of girders with trapezoidal corrugated web plates with cut outs. The study is focused on the local buckling behavior of these girders with web openings. In their paper, Romeijn, Sarkhosh and Hoop [3] present a basic parametric study on steel girders with trapezoidal corrugated webs having cut outs. Finite element analysis is used to investigate the effect of cut outs in corrugated webs. Openings were considered on the flat plate parts of the trapezoidal web and the effect of various geometric parameters on the behavior was investigated in the framework of a parametric study. Kiymaz, Coskun E, Coskun C and Seckin [4] performed a finite element analysis on series of models of beams with sinusoidal corrugation with different corrugation density and different relative opening diameters. In recent years there have been several publications on a similar topic from Malaysia by De'nan and Musnira in 2012 [5], by Krishnarani and Krishna in 2016 [6] and by De'nan, Hasan and Keong in 2017 [7]. In these papers, beams with a triangular corrugated and simultaneously perforated web are considered. In these works, the openings in the web are considered primarily as a way to reduce the weight of the whole structure.

In present work, a numerical parametric study was carried out for simply supported corrugated web beams with web openings in the middle of the span and at distance of $1/6$ of the span from the support. Within the parametric study, various cases were considered including the opening size and the corrugation density expressed as a ratio between height and length of half-wave of corrugation. Models without web openings were also analyzed and results compared with estimations of the

currently available design guidance [8]. Cases with web openings were examined in terms of the effect of varying web opening size and corrugation density on stresses near the opening.

2. Design of triangular corrugated web steel beam

Limit states considered for the design of a corrugated web beam is, in general, similar to those considered for a steel plate girder with a flat web plate. The destruction of steel beam with a corrugated web may occur for several reasons: due to the exhaustion of the load-bearing capacity of flanges at bending or corrugated web at shear; due to local buckling of compressed flange or particular areas of the web; due to overall buckling of the entire structure. In addition, according to the conditions of suitability for normal operation, the maximum vertical deflections of the beam must be limited [8].

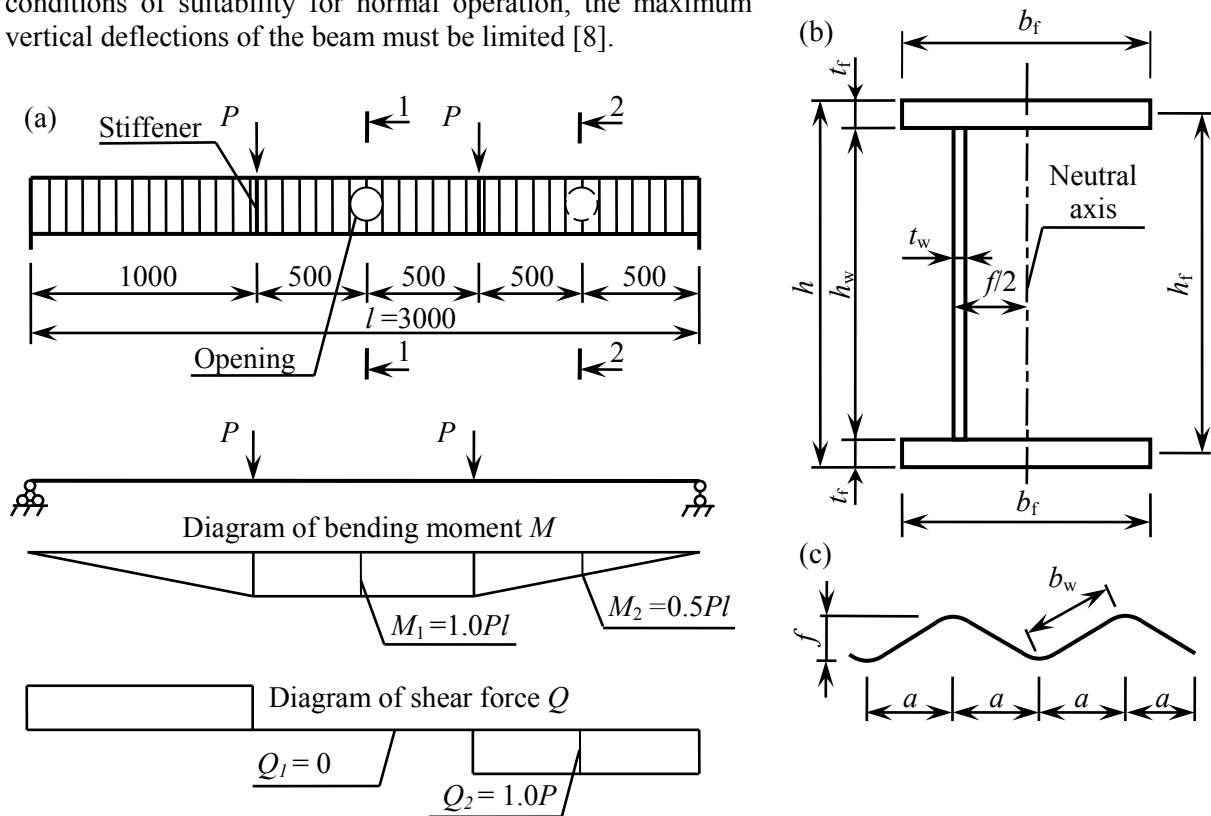


Figure 2. (a) Considered beam design scheme; (b) Cross section of beam with corrugated web; (c) Geometrical parameters of corrugated web with triangular shaped corrugations

Bending resistance of a corrugated beam is given as flange resistances multiplied by the section height and no contribution of the web is taken into account

$$\sigma_f = \frac{M}{b_f \cdot t_f \cdot h_f} \leq R_y \gamma_c \quad (1)$$

in which b_f , t_f , h_f are the flange width, thickness and distance between centers of gravity of compressed and tension flanges respectively, R_y is the material yield strength, $\gamma_c = 1.0$ is working condition factor specified by building code.

On the other hand, shear action is assumed to be carried by the web alone

$$\tau_w = \frac{Q}{0.9 \cdot t_w \cdot h_w} \leq 0.58 \cdot R_y \gamma_c \quad (2)$$

in which t_w , h_w are the corrugated web thickness and height.

The effective stresses in the corrugated web at the zones of the flange weld can be determined from expression

$$\sigma_{ef} = \sqrt{\sigma_f^2 + 3\tau_w^2} \leq R_y \gamma_c. \quad (3)$$

For the corrugated web beam it is necessary to determine the deflection taking into account the effect of transverse forces. For a hinged-supported beam shown on figure 2, the maximum deflection is determined by the formula

$$f = \frac{Pl^3}{28.17EJ} + \frac{Pl}{3Gh_w t_w}, \quad (4)$$

in which P is applied force, l is beam span, $E = 206000\text{MPa}$, $G = 78000\text{MPa}$ and the second moment of area J is made assuming that the entire bending moment in a beam with a corrugated web is perceived only by the flanges

$$J = 0.5b_f t_f h_f^2. \quad (5)$$

3. Numerical parametric study

A numerical parametric study was carried out on simply supported I-beams with triangular corrugated webs. Numerical modelling of the beams was carried out using ABAQUS (2017), a general purpose finite element program. This program can cater for problems ranging from relatively simple linear analyses to non-linear analyses which require consideration of various manufacturing distortions and material non-linearities. A parametric study was performed for a number of models with varying web opening size and corrugation density. The modelling assumptions including the geometry, material, loading and boundary conditions are presented below.

3.1. Description of the FE models

Typical finite element models adopted for the corrugated web beams are shown in figure 3. A type of four-node doubly curved shell element (S4R) which is available in ABAQUS (2017) was employed in the models. A typical model is composed of upper and lower flanges of 10mm x 200mm in size, representing a plate 200 mm wide and 10 mm thick and 4mm x 600mm corrugated web which is a thin sheet of steel plate having 4mm thickness and 600mm height, two end cover plates and a central stiffeners (with plate thickness $t = 10\text{ mm}$) above which point loads $P = 100\text{ kN}$ are applied on sites of 100mm width at the upper flange.

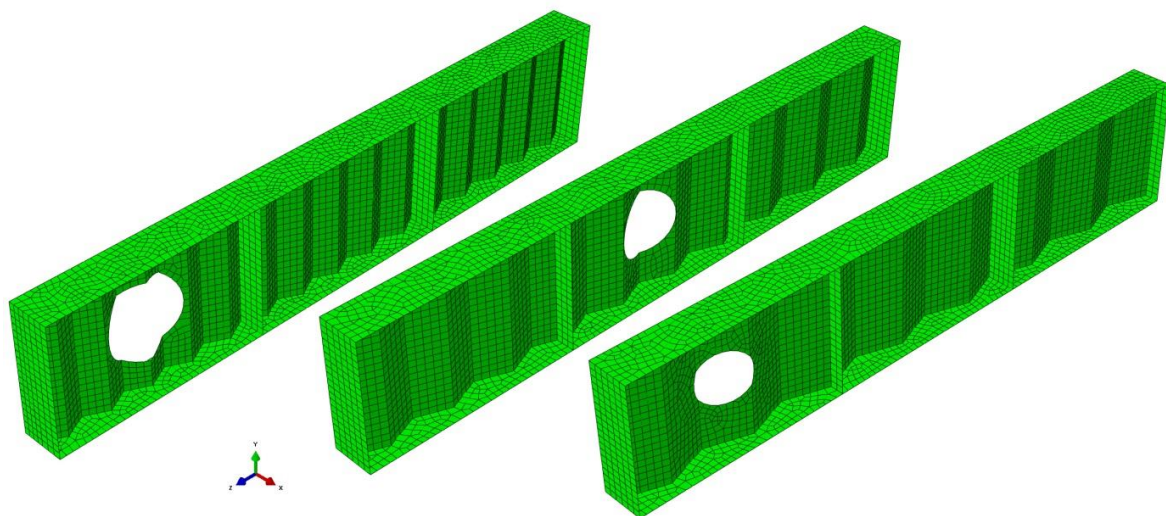


Figure 3. FE models adopted for the analysis of triangularly corrugated web beams with openings

For the webs three different corrugation densities were assumed. As schematically explained in figure 2 the corrugation density is defined as the ratio of the magnitude of the wave height f to the corrugation length a . In the models were used three different corrugation densities: $f/a = 50\text{mm}/100\text{mm}$, $f/a = 60\text{mm}/150\text{mm}$ and $f/a = 70\text{mm}/200\text{mm}$. The corrugation densities adopted in this study represent practical geometries, which are common used for such structures in building practice [8].

In the models, web circular opening is created on one side of the web and in the middle of beam span. The centre of the opening is located 500mm and 1500mm from the left cover plate at the neutral axis of the beam. Within the parametric study, nine different opening sizes were considered which is expressed as the ratio of the opening diameter d to web height h_w . Nine values of d/h_w is equal to 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 were adopted. For example, in case of $d/h_w = 0.2$, a circular opening with a 120 mm diameter is used.

Boundary conditions were applied to either ends of the 3m long beam models at lower flange surface nodes by restraining appropriate degrees of freedom so as to simulate the simply supported condition. An elastic material model was assumed with a yield strength value of 240MPa, modulus of elasticity $E = 206000$ MPa and Poisson's ratio 0.3. Nonlinear geometrical effects are automatically included in the calculation.

3.2. Non-linear FE analysis

The non-linear response of the models described above was examined through finite element analysis. The FE program used in this study (ABAQUS) uses Newton's method to solve the nonlinear equilibrium equations. In this method, the solution is obtained as a series of increments, with iterations to obtain equilibrium within each increment. Following this method, nonlinear static analyses were carried out for the beams in the parametric study.

The numerical parametric study of corrugated web beams as described above includes the analysis of 57 finite element models. Out of these 57 models 3 are beam models with no web opening with three different corrugation densities. 54 models include web openings with different sizes of circular openings as defined above and located at 1/6 of span and at mid-span of beam.

For all beam models, the equivalent tensile stresses in corrugated web at the level of the flange weld of the beam in the section above the opening and the maximum stresses on the contour of the opening are determined. Also for each model, the maximum vertical deflections are determined.

4. Results of the parametric study

In order to evaluate the effect of the opening on the distribution of stresses in the corrugated web, the so-called stress concentration factor k_s and the deflection increase factor k_d are determined by formulas

$$k_s = \frac{\sigma_{\max}}{\sigma_{\text{ef},0}}, \quad (6)$$

$$k_d = \frac{f}{f_0}, \quad (7)$$

in which σ_{\max} is maximum stresses on the contour of the opening, $\sigma_{\text{ef},0}$ is equivalent tensile stresses at the level of the flange weld of the beam in the section above the opening, f is vertical deflection of the beam with opening, f_0 is vertical deflection of the beam without opening.

The values of the stress concentration factors and deflection increase factor in cases of location the opening in zone of pure bending and in zone of transverse bending are given in table 1. Stress concentration factors and deflection increase factors versus web opening size relationships for different corrugation densities are given in figures 4, 5 and 6.

According to the results of FE analysis, the greatest stress concentration occurs on the contour of the opening in areas located at an angle of about 45° to the longitudinal axis of the beam in the case of

transverse bending and in areas located at an angle of 90^0 in the case of pure bending which corresponds to the existing data on this problem.

Table 1. Result obtained from the non-linear parametric study

Model	Opening in zone of pure bending				Opening in zone of transverse bending			
	σ_{\max} (MPa)	k_s	f (mm)	k_d	σ_{\max} (MPa)	k_s	f (mm)	k_d
f/a : 50/100 no opening	85.73 ^a	—	1.95	—	82.71 ^a	—	1.95	—
f/a : 50/100 d/h_w : 0.1	3.03	0.04	1.95	1.00	109.9	1.33	1.95	1.00
f/a : 50/100 d/h_w : 0.2	4.71	0.05	1.95	1.00	237.32	2.87	1.99	1.02
f/a : 50/100 d/h_w : 0.3	6.14	0.07	1.95	1.00	722.61	8.73	2.5	1.28
f/a : 50/100 d/h_w : 0.4	7.96	0.09	1.95	1.00	1441.52	17.41	8.44	4.33
f/a : 50/100 d/h_w : 0.5	9.49	0.11	1.95	1.00	1472.88	17.79	11.67	5.98
f/a : 50/100 d/h_w : 0.6	13.14	0.15	1.95	1.00	1593.01	19.24	15.22	7.81
f/a : 50/100 d/h_w : 0.7	14.27	0.17	1.95	1.00	2970.72	35.87	31.99	16.41
f/a : 50/100 d/h_w : 0.8	21.67	0.25	1.95	1.00	3515.95	42.46	48.58	24.91
f/a : 50/100 d/h_w : 0.9	31.45	0.37	1.95	1.00	3476.45	41.98	65.89	33.79
f/a : 60/150 no opening	88.31 ^a	—	1.93	—	85.26 ^a	—	1.93	—
f/a : 60/150 d/h_w : 0.1	2.89	0.03	1.93	1.00	130.39	1.53	1.94	1.01
f/a : 60/150 d/h_w : 0.2	4.43	0.05	1.93	1.00	275.68	3.23	2.01	1.04
f/a : 60/150 d/h_w : 0.3	5.52	0.06	1.93	1.00	1103.12	12.94	2.65	1.37
f/a : 60/150 d/h_w : 0.4	7.5	0.08	1.94	1.01	2180.67	25.58	10.62	5.50
f/a : 60/150 d/h_w : 0.5	10.1	0.11	1.94	1.01	1570.4	18.42	15.42	7.99
f/a : 60/150 d/h_w : 0.6	12	0.14	1.94	1.01	1338.11	15.69	18.74	9.71
f/a : 60/150 d/h_w : 0.7	18.29	0.21	1.94	1.01	2258.06	26.48	27.56	14.28
f/a : 60/150 d/h_w : 0.8	24.23	0.27	1.94	1.01	4172.9	48.94	41.95	21.74
f/a : 60/150 d/h_w : 0.9	50.42	0.57	1.95	1.01	4227.33	49.58	67.28	34.86
f/a : 70/200 no opening	86.7 ^a	—	1.89	—	80.4 ^a	—	1.89	—
f/a : 70/200 d/h_w : 0.1	4.02	0.05	1.89	1.00	101.66	1.19	1.9	1.01
f/a : 70/200 d/h_w : 0.2	5.05	0.06	1.89	1.00	190.24	2.23	1.93	1.02
f/a : 70/200 d/h_w : 0.3	6.25	0.07	1.89	1.00	1070.88	12.56	2.51	1.33
f/a : 70/200 d/h_w : 0.4	9.5	0.11	1.89	1.00	2216.35	26.00	11.43	6.05
f/a : 70/200 d/h_w : 0.5	14.89	0.17	1.89	1.00	1787.52	20.97	18.99	10.05
f/a : 70/200 d/h_w : 0.6	18.88	0.22	1.89	1.00	1896.82	22.25	24.66	13.05
f/a : 70/200 d/h_w : 0.7	19.35	0.22	1.89	1.00	2056.21	24.12	29.47	15.59
f/a : 70/200 d/h_w : 0.8	27.76	0.32	1.9	1.01	2162.58	25.36	34.92	18.48
f/a : 70/200 d/h_w : 0.9	50.03	0.58	1.9	1.01	3916.69	45.94	50.09	26.50

^a For beams without opening specified equivalent stresses in corrugated web at the level of flange weld

The arrangement of the opening in zone of pure bending has practically no effect on the bearing capacity and deformation property of the beam – the stress concentration factor k_s in this case did not exceed the value of 0.58 and the deflection increase factor k_d did not change at all and was approximately equal to 1.0.

There is quite different situation in zone of transverse bending, which is closest to the operation conditions for real beam structures. The opening in the corrugated web sharply reduces the bearing capacity of the beam and significantly increases its deflection. Moreover the beam deflection up to value of relative diameter $d/h_w = 0.3$ practically does not increase, and then increases exponentially. The reduced stresses in the web already at values of $d/h_w = 0.2$ can lead to the appearance of zones of

plasticity along the perimeter of the opening. Such situation can lead to the appearance of a crack and to the progressive destruction of the entire structure. For practical design situations, it may be advisable to avoid making openings in the transverse bending zones of a beam with a corrugated web or to perform additional reinforcement of areas with such openings.

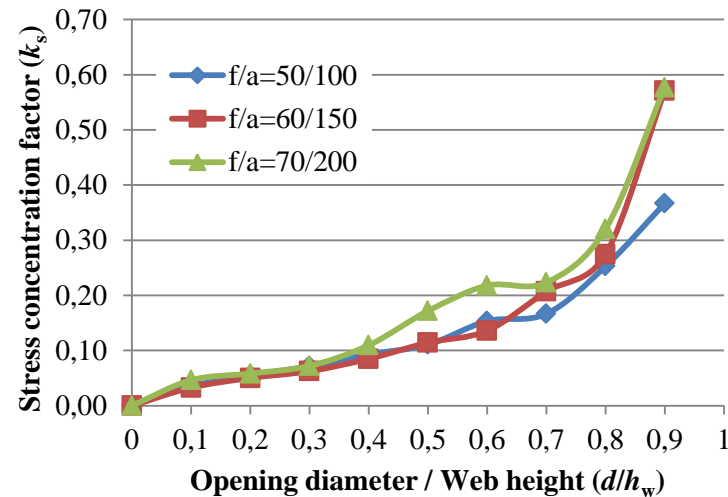


Figure 4. Stress concentration factors versus web opening size relationships in case of opening in zone of pure bending

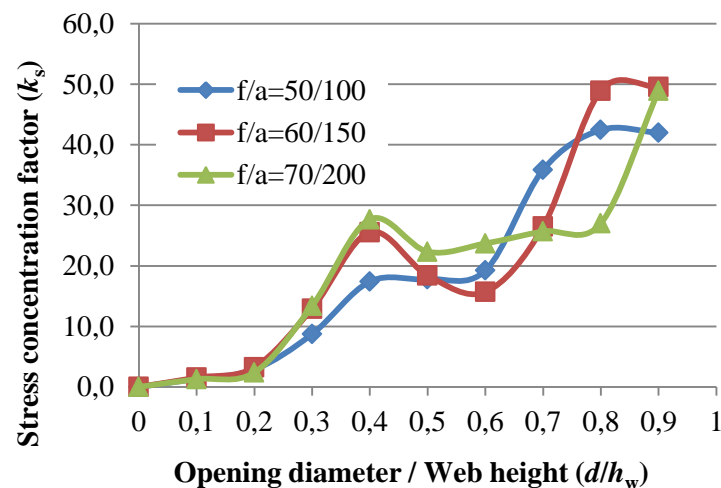


Figure 5. Stress concentration factors versus web opening size relationships in case of opening in zone of transverse bending

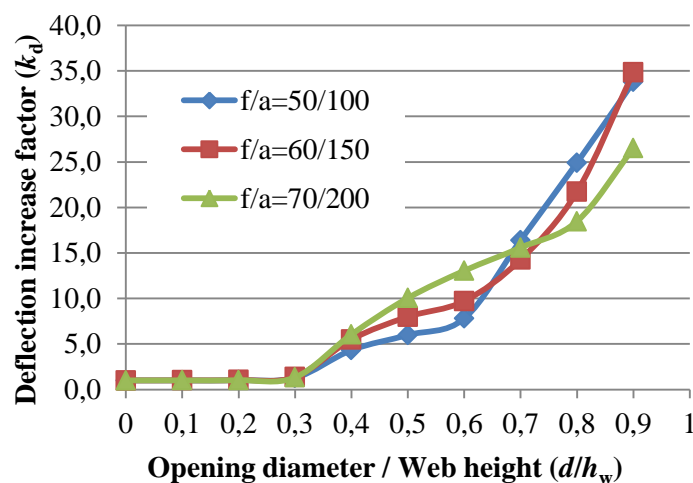


Figure 6. Deflection increase factors versus web opening size relationships in case of opening in zone of transverse bending

Some singularity between values of the stress concentration factors k_s for the range of openings $d/h_w > 0.4$ is explained by the apparent modification of the beam design by such large openings in the corrugated web and transformation of the whole structure into a peculiar Vierendeel truss with corresponding redistribution of stresses.

5. Conclusions

In present work an investigation into the behavior and design of triangular corrugated steel web beams with web openings was carried out. A general purpose finite element analysis program was used to model steel beams with varying web opening sizes and corrugation densities. Using this program, a numerical parametric study was carried out for simply supported corrugated steel web beams of 3 m span and with web openings at the middle of the span and at point 1/6 span from support. Within the parametric study were considered different opening size and the corrugation density of the web. The chosen models represented practical geometries in terms of production and structural application.

According to the results of the performed work, it is recommended for practical design to avoid cutting openings in the sections of the beams near supports, in zones of transverse bending or in areas with significant shear stresses. If it is necessary to make an opening in such zone, it is recommended to strengthen that section with additional rib of stiffness and edging its contour with sheet or corner steel. It is possible to make openings in corrugated web beams in areas of pure bending or in areas with minimal shear stresses. In this case, it is generally possible to avoid additional reinforcement of the opening.

To evaluate the load-bearing capacity of a corrugated web, weakened by a circular opening, it is possible to use the expressions (3) and (4) multiplying the values of stresses and deflections by the corresponding factors k_s and k_d given in this paper.

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